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RESEARCH ARTICLE

Changes in the firmness and other quality parameters of fresh-cut 'Maradol' papaya treated with additives and 1-methylcyclopropene

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ABSTRACT

This study aimed to evaluate the effect of 1-methylcyclopropene (1-MCP) applied as pre-cutting, post-cutting, and double application (before and after cutting) on the changes in the firmness and quality parameters of fresh-cut ripe 'Maradol' papaya. Four treatments (T1-T4) were used. T1 (Control treatment): Fresh-cut 'Maradol' papaya slices (Control treatment or T1) dipped in 1% $CaCl_2$ for 2 min, then sprayed with 0.1% iso-ascorbic acid and 0.05% sorbic acid. One part of the T1 slices were treated with 1000 nL/L of 1-MCP for 12 h at 10 °C (T2). T3: Fresh-cut papaya slices treated with the same additives from the whole papaya treated 1000 nL/L of 1-MCP for 12 h at 20 °C. T4: Fresh-cut papaya with additives treated with 1-MCP before and after cutting. All slices were packed in polypropylene trays with a perforated cover and stored at 4 ºC. T3 and T4 slices exhibited lower firmness loss and decreased activity of pectin methylesterase, polygalacturonase, and β-galactosidase compared to T1 and T2 slices. Moreover, T3 and T4 slices had low translucency and microbial load, complying with the European Union limit (3 log CFU/g). No significant variations in acidity, pH, and total soluble solids were noted between treatments, but higher color values were obtained in T3 and T4 slices. To the best of our knowledge, this is the first study where the combining effects of additives and 1-MCP application before and after cutting extended the shelf-life of fresh-cut 'Maradol' papaya for up to 13 days at 4 °C, twice the duration reported by others.

Keywords: *Carica papaya*, Postharvest, Translucency, Quality, Shelf-life

INTRODUCTION

Papaya (*Carica papaya* L.) is a tropical fruit with a pleasant flavor, nutritional and digestive properties. The world production of papaya is in 60 countries, with 165,911 tons per year, and Mexico ranks fifth place, with 1,134,753 tons (FAO, 2021). This fruit is the third most consumed tropical fruit worldwide, so it becomes one of the most important from economic and social points of view. In addition, it is a low-calorie fruit, laxative and with high content of antioxidants such as carotenoids and vitamins (Zhou et al., 2023).

Although papaya fruit is commonly consumed fresh and industrialized to produce purees (Relox et al., 2015), the production is greater than the demand. It is because papaya fruit is highly perishable by being a climacteric fruit. The physiological changes during storage are fast, and there is a loss of weight, excessive softening and high microbial growth (Salvador-Figueroa et al., 2017; Salehi, 2020). Therefore, it is necessary to explore alternatives such as fresh-cut or minimally processed products (Relox et al., 2015). The consumption and marketing of fresh-cut or minimally processed products have increased worldwide as ready-to-eat foods, including fresh-cut fruits, are becoming popular. However, obtaining fresh-cut fruit and vegetables with acceptable quality and long shelf life is challenging (Koyuncu, 2020).

Minimal processing or fresh cutting induces several physiological alterations, which must be minimized to

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reduce deterioration. In fresh-cut papaya, the major obstacle is the limited shelf-life, mainly due to excessive softening and browning of the tissues on the cutting surface (Tabassum and Khan, 2020). Research is still needed to design and implement methods to improve the process and preserve the quality of these highly perishable products, such as using additives combined with ethylene antagonists.

The shelf life of fresh-cut papaya has been widely studied using refrigerated temperatures (Falah et al., 2015), citral-nanoemulsion (Luciano et al., 2022) and different edible coatings in combination with additives (Tabassum and Khan, 2020; Rong et al., 2022; Sekarina et al., 2023). Additives are widely used in the food industry to prevent, retard or mask alterations produced in foods. Among the most commonly used additives are antioxidants, acidulants, sugars, salt, and antimicrobials, all of which can serve in minimally processed fruits and vegetables to prevent loss of firmness, browning reactions and to protect products against loss of flavor and odor, loss of nutritional value, and extension of shelf life (Soliva-Fortuny and Martín-Belloso, 2003). However, the shelf life of fresh-cut papaya has not been more than 10 days in refrigeration.

On the other hand, the 1-Methylcyclopropane (1-MCP) application is another method used to extend the shelf life of fresh-cut fruits because it is an effective ethylene inhibitor (Blankenship and Dole, 2003). It has been demonstrated that 1-MCP delays ripening in many horticultural commodities. 1-MCP reduces the loss of firmness in intact papaya fruit, decreasing the polygalacturonase (PG), β-galactose (β-Gal), and pectin methylesterase (PME) activities (Zerpa-Catanho et al., 2017; Zhu et al., 2019). However, some studies have suggested that 1-MCP did not extend the shelf life of fresh-cut papaya. Ergun et al. (2006) and Ergun et al. (2011) reported that 1-MCP applied on intact and fresh-cut 'Sunrise Solo' papaya did not reduce the loss of firmness. On the other hand, 1-MCP post-cutting application on fresh-cut 'Sinta' papaya decreased PG activity and ethylene production, and the slices complied with the recommended limits in total coliforms, mesophilic aerobic bacteria, molds, and yeasts counts; however, the shelf life of the slices was only six days at 4 °C (Relox et al., 2015). It can be due to the 1-MCP effect on fresh-cut fruits depending on the cutting method, maturity stage, concentration, exposition time, combination with additives, type of fruit, varieties, and single or repeated application (Xu et al., 2023).

Actual references on the effect of 1-MCP combined with additives on fresh-cut papaya were not found; however, in fresh-cut peaches with 1-MCP (1 μL/L) before cutting combined with phytic acid after cutting, it was reported that firmness and volatile aroma were maintained for 10 days at 0 °C (Jiang et al., 2023). Xu et al. (2023) reported that 1-MCP combined with ethephon decreased the levels of flavonoids, oxidation, and weight loss of Chinese water chestnut for 5 days at 10 °C. Therefore, the effect of 1-MCP in combination with other products on minimally processed fruits must be evaluated for each type of fruit. The objective of this work was to assess the impact of 1-MCP application (pre-cutting, post-cutting, and double application, before and after cutting) combined with additives on changes in the firmness and other quality parameters of fresh-cut 'Maradol' papaya.

MATERIALS AND METHODS

Sample preparation

'Maradol' papaya fruit (orange peel color and 26 N of firmness) were purchased from a local market in Tepic, Nayarit, Mexico, washed with chlorinated water (50 mg/L) for 5 min, and dried. Fruits were then stored for 2 h at 5 °C before cutting. Then, cold hydrogen peroxide (2%) was sprayed on the fruit, left to dry, and the skin was removed. Finally, the slices were made in a rectangular shape of 1x5x2.5 cm (thickness x length x width). Figs. 1 and 2 show the experimental diagram and photographs of different process steps.

Treatments

Fresh-cut papaya with additives or control (T1)

The slices were dipped in 1% $CaCl_2$ for 2 min, then sprayed with 0.1% iso-ascorbic acid as an antioxidant and, finally, with 0.05% sorbic acid as an antimicrobial agent. The excess solution was allowed to drip off for 30 s before the second dip. Afterwards, the slices were packed in polypropylene trays (8 cm × 10 cm × 4 cm) with a perforated cover (perforations of 2 mm diameter) and stored at 4 °C until analysis.

Fresh-cut papaya with additives and 1-MCP (T2)

The same methodology was followed for applying additives in the slices as in T1. Then, the slices were placed on grids to separate them from each other. The grids were placed in 20 L glass chambers. According to the AgroFresh Inc. (PA, USA) methodology, the concentration of 1000 nL/L was achieved using 13.5 mg of 1-MCP (SmartFresh™ Technology with 3.3% active ingredient) and 1.45 mL of distilled water in a flask with a cap. The mixture was placed in the chamber and immediately sealed for 12 h at 10 °C. Afterwards, the slices were packed and stored at 4 °C, as in T1.

Fresh-cut papaya with additives from whole papaya treated with 1-MCP (T3)

The 1-MCP treatment of whole intact papaya fruit was applied at 20 °C on the same day of harvest. First, exposure to 1-MCP (1000 nL/L diluted in distilled water) for 12 h was made in a 225 L chamber equipped with a fan to homogenize

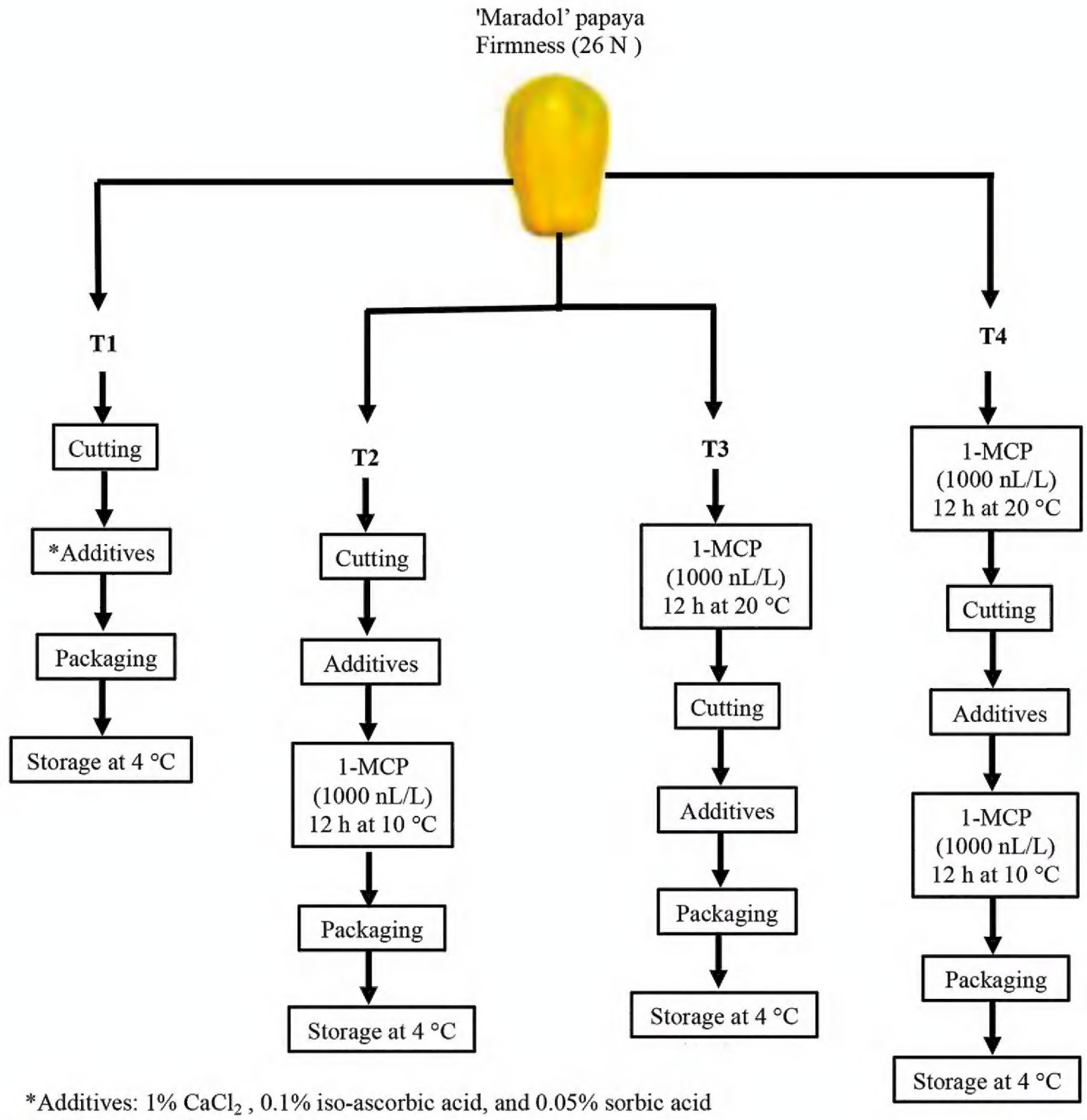

Fig 1. General diagram of the development of the experiment.

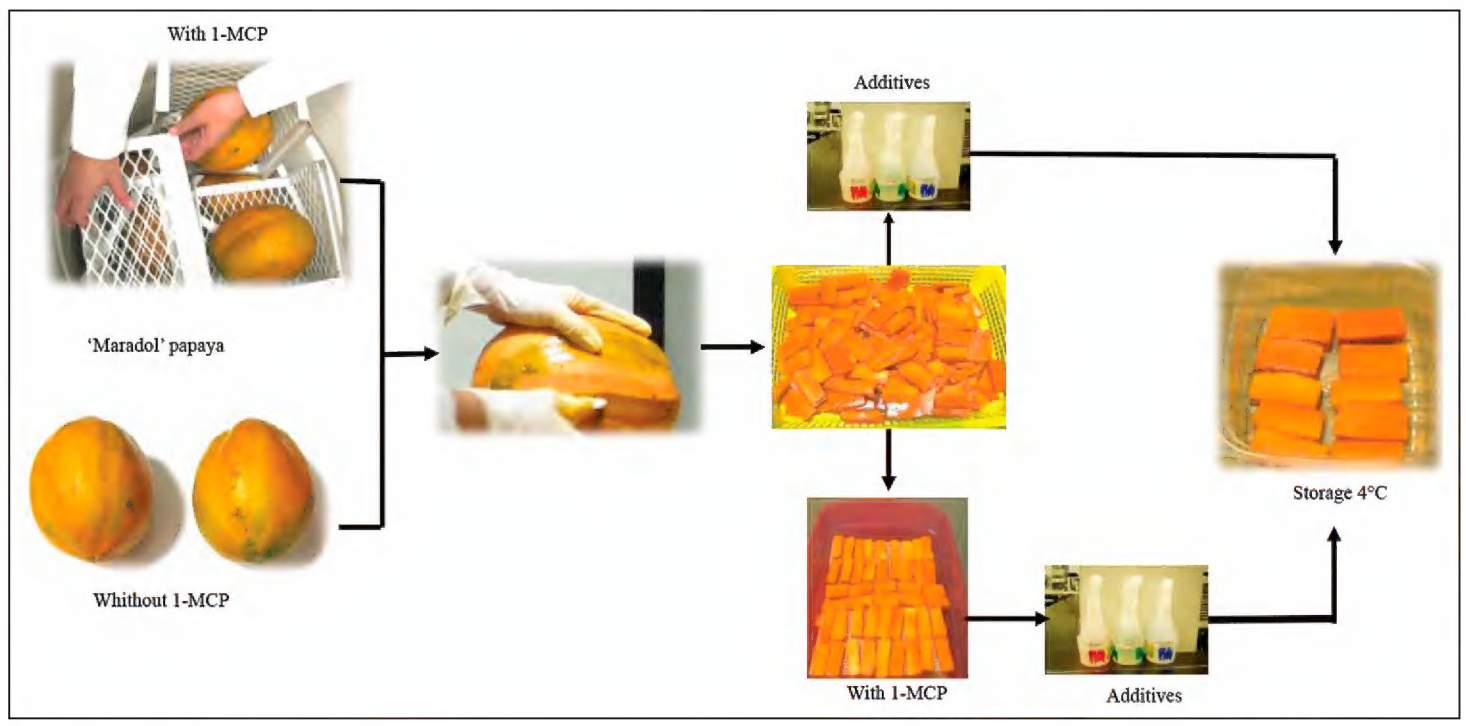

Fig 2. Photographs of different process steps.

the release of 1-MCP. Afterwards, the fruit was stored at 5 °C for 2 h before cutting and disinfected with 2% hydrogen peroxide. Finally, the generated slices were treated with the additives mentioned in T1, packed, and stored at 4 °C.

Fresh-cut papaya with additives treated with 1-MCP before and after cutting (T4)

1-MCP (1000 nL/L) was applied to the whole intact papaya fruit for 12 h at 20 °C (as in T3). Subsequently, the same

methodology was followed to cut the slices and apply additives (as in T1). Then, the slices were treated with 1-MCP (1000 nL/L) for 12 h at 10 °C (as in T2), and finally, the slices were packed and stored at 4 °C.

Firmness, pectin methylesterase, polygalacturonase, and β-galactosidase activities

In the first stage, the firmness and microbiological quality changes were evaluated in all treatments (T1-T4).

Tissue firmness was measured on 20 slices in each treatment using a manual penetrometer (Shimpo FGV-50, Lincolnwood, USA) with a 10 mm cylindrical probe and reported in Newtons (N).

Enzymatic extraction was carried out at 4 °C. Homogenized papaya slices (10 g) were mixed with 20 mL of 0.1 M sodium citrate buffer (pH = 4.6), containing 1 M NaCl, 0.5% (w/v) polyvinylpyrrolidone and 10 mM β-mercaptoethanol. The mixture was subjected to a magnetic stirrer for 30 min and centrifuged at 12,600 *x g* for 30 min. The supernatant was used as an enzymatic extract for all enzyme activities (Lazan et al., 1995).

Pectin methylesterase (PME) activity was determined by the method described by Montalvo et al. (2009). The reaction was carried out with 2 mL of 0.5% pectin as substrate, 0.15 mL of bromothymol blue, and 0.83 mL of deionized water. This mixture was incubated at 37 °C for 15 min, then 0.02 mL of enzymatic extract was added and allowed to react for 1 h. The absorbance was measured at 620 nm in a spectrophotometer (Jenway Model 6705, Felsted, United Kingdom). An activity unit (U) was defined as μM galacturonic acid released per min at 37 °C.

For the polygalacturonase (PG) activity, enzymatic extract (1 mL) was mixed with 2 mL of polygalacturonic acid solution (0.2%) and 0.4 mL of 0.2 M acetate buffer at pH 4.40, previously incubated for 10 min at 37 °C. Then the reaction mixture was incubated for 20 min at 37 °C. Subsequently, 3 mL of 0.2 M sodium borate buffer and 100 μL of 1 % cyanoacetamide were added to the mixture to stop the reaction. It was heated in a water bath for 10 min, cooled, and finally, the absorbance was measured in a spectrophotometer at 276 nm (Montalvo et al., 2009). An activity unit (U) was defined as μM galacturonic acid released per min at 37 °C.

For the measurement of β-galactosidase (β-GAL) activity, the reaction mixture consisted of 0.52 mL of 0.1 M sodium citrate buffer (pH = 4.10) and 0.4 mL of 13 mM p-nitrophenyl-β-D-galactopyranose as substrate. This mixture was incubated at 37 °C for 10 min, then 0.08 mL of the enzyme extract was added and allowed to react for 15 min at the same temperature. Two mL of 0.2 M sodium carbonate was added to stop the reaction, and the absorbance was measured at 415 nm (Lazan et al., 1995). An activity unit (U) was defined as μM p-nitrophenol released per min at 37 °C.

Protein determination in the enzymatic extracts was carried out by the method of Bradford (1976), and the results of all enzyme activities were reported as specific activity (U/mg of protein).

Translucency

A spectrophotometer (Ocean Optics, Red Tide USB650, Duiven, Netherlands) with optical fibers and a 400 μm diameter core was used. The translucency measurements were done in complete darkness, and a tungsten-halogen lamp was used as a light source projecting on three different areas of the slice. The transmittance percentage at 700 nm was measured on ten slices per replicate of each treatment.

Microbiological analysis

Aerobic mesophilic bacteria (AMB), yeast, and mold counts were performed according to the microbiological methods of Downes and Ito (2001). Results were expressed as log colony-forming units per gram of sample (log CFU/g).

Titratable acidity, pH, total soluble solids, color, and sensory analysis

For a second stage, control fresh-cut papaya (T1) and the selected two treatments with 1-MCP (T3 and T4) were compared, evaluating the changes in physicochemical parameters and sensory analysis.

Titratable acidity (TA) was measured using an automatic titrator (SCHOTT Instruments; Berlin, Germany), and the results were reported as the percentage of citric acid (Method 942.15) (AOAC, 2005). The pH values were measured directly in homogenate pulp using a pH meter (HANNA Instruments Ltd, HI 221, Bedford, UK). Total soluble solids (TSS) were determined with a refractometer (Abbe 315RS, Royal Tunbridge Wells, UK) (Method 932.12, AOAC, 2005), and data are expressed in °Brix. The color was determined on the surface of the samples using a Minolta CR-300 colorimeter (Konica Minolta CR-400, Osaka, Japan), and the results were reported as Hue angle (°Hue), Luminosity (L*), and Chroma (C*) values.

For the sensory analysis, the level of satisfaction test (taste, color, odor, and texture) was utilized with 30 untrained judges for T1, T3, and T4 treatments stored for 10 days at 4 °C. The scale was 1–5, where 1 = Dislike it very much,

2 = Slightly dislike it, 3 = Neither like nor dislike it, 4 = Like it slightly, and 5 = Like it very much. For the taste test, the eyes of the judges were covered with cellophane lenses (Pedrero and Pangborn, 1997).

Statistical analysis

A one-factorial experimental design was used. All data were analyzed by analysis of variance (ANOVA) with a 1 or 5% significance level. Tukey´s multiple tests were used for means comparison (α = 0.05 and 0.01). Statistical analysis was performed using Statistical Analysis System (SAS) v.8.0 software.

RESULTS AND DISCUSSION

Changes in firmness, translucency, and microbiological quality

Firmness decreased in all slices throughout the storage period (Fig. 3a). However, T1 had the lowest firmness (10.15 N) at 13 days. Therefore, immersion in $CaCl_2$ was not sufficient to maintain the firmness of fresh-cut papaya. The accelerated firmness loss in fresh-cut 'Maradol' papaya is attributed to changes induced by damage to tissue cells during peeling and cutting, in addition to pectinolytic and proteolytic enzymes released from damaged cells. The transformation of protopectin to water-soluble pectins decreases cellulose crystallinity, diffusion of sugars into intercellular spaces, thinning of cell walls, and movement of cell wall ions (Soliva-Fortuny and Martín-Belloso, 2003).

T2 exhibited a firmness (16.64 N) higher than T1 at the end of storage ($p<0.05$). The $CaCl_2$ application followed by 1-MCP after cutting slowed the changes in firmness as a result of the minor activity of hydrolytic enzymes compared with T1. Both compounds act synergistically on firmness retention. Softening decreased when the $CaCl_2$ and 1-MCP were applied after processing fresh-cut jackfruit (Vargas-Torres et al., 2017).

T3 and T4 treatments had approximately 50% and 15% higher firmness than T1 and T2, respectively ($p<0.05$). The application of 1-MCP before cutting and both before and after cutting of 'Maradol' papaya could decrease the ethylene production rate in a more significant proportion than T2, which in turn had a minor hydrolytic activity in the cell wall. These results coincide with Ergun et al. (2006), who evaluated the effect of 1-MCP (2500 nL/L of 1-MCP for 24 h at 20 °C) on the whole 'Sunrise' papaya. They observed that slices from treated fruit at 5 °C maintained

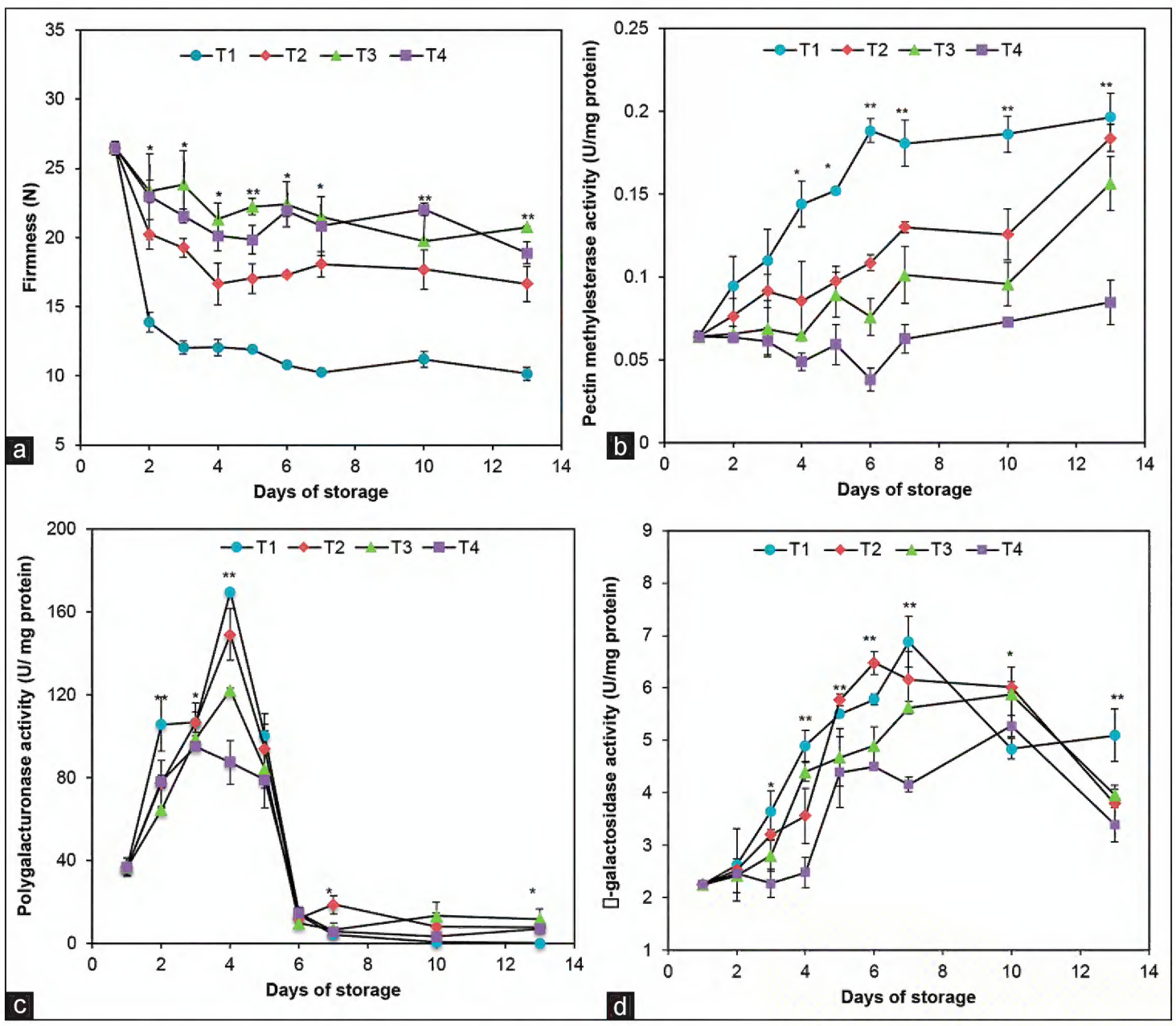

Fig 3. Firmness (a), pectin methylesterase (b), polygalacturonase (c), and β-galactosidase (d) activities in fresh-cut `Maradol´ papaya with additives (T1), fresh-cut papaya with additives and 1-MCP (T2), fresh-cut papaya with additives from fruit treated with 1-MCP (T3), and fresh-cut papaya with additives treated with 1-MCP before and after cutting (T4). *p<0.05, ** p<0.01.

high firmness and had a longer shelf-life than untreated fruit. Similarly, Kızıldeniz et al. (2023) reported that fresh-cut mulberry fruit treated with 1-MCP (before cutting) protected quality and enlarged the shelf life.

Figs. 3b-3d demonstrate the changes in activities of the enzymes related to the firmness loss (PME, PG, and β-GAL) in fresh-cut 'Maradol' papaya. The activity of these enzymes seems to be depended on the treatments used. The highest PME, PG, and β-GAL activities were observed in T1 during storage (Fig. 3b-3d), followed by T2>T3>T4 ($p<0.05$), coinciding with the firmness loss.

PME hydrolyzes the ester bonds of the methyl groups of the polygalacturonic chains, originating free carboxylic groups that intervene in the pH self-regulating effect. In addition, the hemicellulose, cellulose and pectins hydrolyzed by cell wall degrading enzymes such as PG, cellulase and β-GAL producing sugars and free organic acids, which weaken the cell wall and fruit consistency (Xiong et al., 2023). Therefore, it is associated with the degradation of the middle lamella of the cells, which favors the loss of adhesiveness and consistency in fruits (Xiong et al., 2023).

The increased activity of the three enzymes in T1 is probably due to significant ethylene production that induces hydrolysis of the cell wall (He et al., 2021). Nonetheless, the effect of 1-MCP on these hydrolytic enzymes in ascending order was: both before and after cutting > before cutting > after cutting. The best 1-MCP response to these enzyme activities was in T4, probably because 1-MCP had contact with ethylene receptors in the whole fruit and the slices, and its antagonistic action was extended. Therefore, ethylene production may be lower in this condition than in the others, thus decreasing cell wall degradation. PG activity and ethylene production were reduced in fresh-cut 'Sinta' papaya from whole intact papaya fruit treated with 1-MCP (Relox et al., 2015). It has been demonstrated that 1-MCP decreases the expression of genes coding for these enzymes (Zhu et al., 2019).

The translucency process increased regardless of the treatment, with significant differences among them ($p<0.05$) (Fig. 4). T1 presented the highest percentage of translucency (17.87%), followed by T2 (12.52%), T3 (6.85%), and T4 (7.14%). The results are related to firmness loss (Fig. 3).

A translucency percentage of up to 15% in fresh-cut papaya is considered commercially unacceptable (Rivera-López et al., 2004). Therefore, T2-T4 slices did not exceed 15% translucency, except for T1 slices. Translucency is a physiological disorder that reduces water in intracellular spaces when there is a firmness loss and consequently

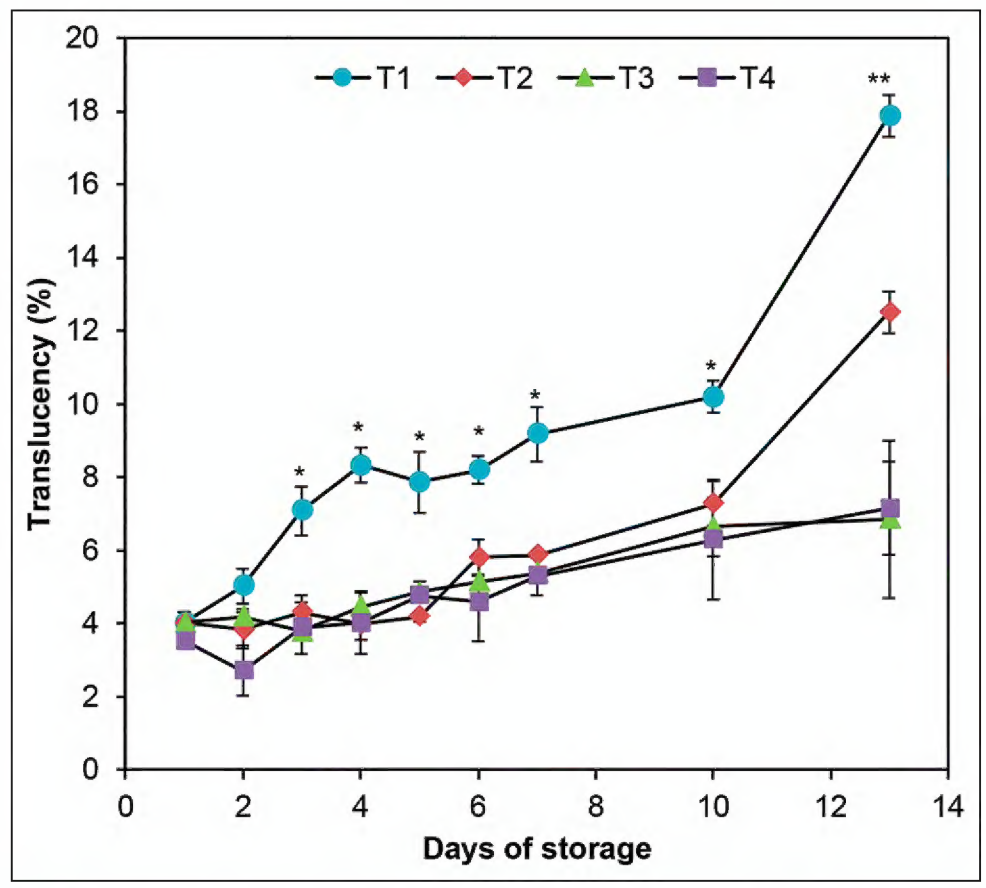

Fig 4. Translucency of fresh-cut papaya treated with additives (Control, T1), fresh-cut papaya with additives and 1-MCP (T2), fresh-cut papaya with additives from whole intact papaya treated with 1-MCP (T3), and fresh-cut papaya with additives treated with 1-MCP before and after cutting (T4). *$p<0.05$, ** $p<0.01$.

loses cellular turgescence, causing soaking (de Oliveira and Vitória, 2011). Murai et al. (2021) concluded that cutting induces the development of translucency in cut pineapple. However, it decreases due to storage at low temperatures (4-5 °C) and the packaging (Brecht, 2020).

The low translucency values of T3 and T4 could be attributed to the application of 1-MCP after and before cutting, which delayed the appearance of this physiological disorder by decreasing ethylene production and thus reducing the loss of firmness. The development of translucency or water-soaking is related to tissue softening (Tadeo et al., 2018). No water-soaking incidence was recorded throughout storing of the 1-MCP-treated fresh-cut red dragon fruit (Tadeo et al., 2018).

Ergun et al. (2006) evaluated translucency in `Sunrise Solo´ papaya slices from untreated or treated with 1-MCP whole fruits. They reported that papaya slices from untreated whole papaya showed higher ethylene production than those from treated whole papaya. In addition, papaya slices from untreated fruit developed higher translucency than slices from fruit treated with 1-MCP. The authors concluded a relationship between ethylene production, loss of firmness, and the development of translucency because ethylene controls the enzymes that degrade the cell wall; at the same time, this degradation causes water-soaking.

No coliforms were detected throughout storage; however, the population of aerobic mesophiles increased during storage (Table 1). On the other hand, molds and yeasts

had no growth until 10 and 13 days of storage, respectively. Moreover, significant differences were found between treatments ($p<0.01$). Cutting and peeling processes promote the growth of microorganisms, thus shortening fresh-cut fruits' shelf life due to cutting might cause high availability of nutrients providing favorable conditions for the development of microorganisms (Wang et al., 2022).

Means of three replicates ± standard deviation. Uppercase letters (A, B, C, etc.) indicate significant differences between days of storage. Lowercase letters (a, b, c, etc.) indicate significant differences between treatments ($p<005$). NG = No Growth. T1 = Control fresh-cut papaya with additives (1% $CaCl_2$, 0.1% iso-ascorbic acid and 0.05% sorbic acid). T2 = Fresh-cut papaya with additives and 1-MCP (1000 nL/L, 12 h at 10 °C). T3 = Fresh-cut papaya with additives from whole papaya treated with 1-MCP (1000 nL/L, 12 h at 20 °C). T4 = Fresh-cut papaya with additives treated with 1-MCP before and after cutting.

Moreover, it has been demonstrated that ethylene-induced microbial growth is indirect. When fruits are cut, the ethylene production is accelerated, and at the same time, this gas accelerates the ripening. Consequently, polysaccharides are degraded, and the products are substrates of microorganisms (Castillo-Israel et al., 2015).

1-MCP application before cutting and both before and after cutting of 'Maradol' papaya (T2, T3, and T4) reduced microbial growth (Table 1). Low aerobic plate count, molds and yeast counts, and no coliform count were reported in fresh-cut papaya (Ergun et al., 2006), fresh-cut red and white dragon fruit (Tadeo et al., 2018), fresh-cut pineapple (Bernardino et al., 2016), fresh-cut mango (Castillo-Israel et al., 2015) with the post-cutting application of 1-MCP. It can be discussed because 1-MCP could counteract microbial growth by inhibiting ethylene production (Castillo-Israel et al., 2015). In addition, the conservation of firmness decreases water availability and a pH of 5.4 delays microbial growth (Tadeo et al., 2018).

The European Union considers a limit of 3 log CFU/g for *E. coli* (EC/2073.2075) in fresh-cut fruits and vegetables (Graffham, 2006). Likewise, Spanish authorities set limits of 7, 5, and 3 log CFU/g for aerobic bacteria, yeasts, and mold counts on minimally processed fruits for safe consumption (Raybaudi-Massilia et al., 2007; Barth et al., 2009). Our results have shown that the total count of aerobic mesophiles, molds, and yeast in fresh-cut `Maradol´ papaya (four treatments) was lower than the limits described. The reported shelf life of fresh-cut 'Sunrise Solo' papaya stored at 5 to 10 °C was approximately 6 days (Ergun et al., 2006). Still, in our work, the shelf life of fresh-cut 'Maradol' papaya treated with 1-MCP before (T3) and both before and after (T4) cutting was 10-13 days at 4 °C, and therefore these treatments were selected for the second stage.

Changes in physicochemical parameters and sensory analysis

A slight increase in TA was observed during the storage of papaya fruit slices, from 0.03 to 0.076 % citric acid (Table 2), with significant differences between treatments ($p<0.05$). Similar results were reported in fresh-cut celery treated with 1-MCP (Massolo et al., 2019). The slight increase in TA can be explained by the formation of organic acid in the process of cell wall degradation during the ripening process, in addition to the release of organic acids by cutting (Xiong et al., 2023). Nonetheless,1-MCP delayed the increase of TA in T3 and T4. It is due to the low respiration rate and low firmness loss (Relox et al., 2015;). Although, several studies indicate that treatment with 1-MCP does not provide an additional or consistent effect on the titratable acidity of some fruits, depending on the species, variety, and storage conditions (Massolo et al., 2019).

The pH of samples slightly decreased, coinciding with the behavior of TA (Table 2). Depolymerization of pectins can release galacturonic acids and simultaneously slightly reduce the pH (Xiong et al., 2023).

Table 1: Microbiological analysis (Log CFU/g) of fresh-cut 'Maradol' papaya fruit stored at 4°C, with or without applied 1-methylcyclopropene (1-MCP)

Treatments	Days of storage				
	1	4	7	10	13
			Aerobic mesophilic bacteria		
T1	2.43 ± 0.05^{aA}	3.61 ± 0.21^{aB}	3.59 ± 0.01^{aB}	4.04 ± 0.02^{bD}	4.47 ± 0.02^{aC}
T2	2.41 ± 0.06^{aA}	3.17 ± 0.02^{bB}	3.50 ± 0.04^{aC}	3.57 ± 0.12^{aB}	4.32 ± 0.07^{aE}
T3	2.39 ± 0.04^{aA}	2.56 ± 0.04^{cB}	2.83 ± 0.05^{bC}	3.23 ± 0.03^{cD}	4.11 ± 0.05^{bE}
T4	2.40 ± 0.07^{aA}	2.59 ± 0.03^{cA}	2.23 ± 0.01^{cA}	3.27 ± 0.04^{cB}	4.14 ± 0.03^{bC}
			Molds and yeasts		
T1	NG	NG	NG	1.69 ± 0.04^{aA}	2.01 ± 0.06^{bB}
T2	NG	NG	NG	2.02 ± 0.03^{bA}	2.07 ± 0.01^{aA}
T3	NG	NG	NG	1.69 ± 0.02^{aA}	1.84 ± 0.01^{bB}
T4	NG	NG	NG	1.60 ± 0.03^{cA}	1.74 ± 0.02^{bB}

Table 2: Physicochemical parameters of fresh-cut 'Maradol' papaya stored at 4°C, with or without 1-methylcyclopropene application.

Treatments	Days of storage						
	1	3	5	7	9	11	13
				Titratable acidity (% citric acid)			
T1	0.03 ± 0.001^{dA}	0.034 ± 0.002^{dA}	0.038 ± 0.002^{cA}	0.040 ± 0.001^{cA}	0.064 ± 0.002^{bA}	0.072 ± 0.001^{aA}	0.076 ± 0.001^{aA}
T3	0.03 ± 0.001^{cA}	0.031 ± 0.001^{cA}	0.035 ± 0.001^{cA}	0.039 ± 0.002^{bA}	0.053 ± 0.001^{aB}	0.060 ± 0.001^{aB}	0.066 ± 0.001^{aB}
T4	0.03 ± 0.001^{cA}	0.030 ± 0.002^{cA}	0.034 ± 0.001^{cA}	0.037 ± 0.001^{bA}	0.051 ± 0.001^{aB}	0.058 ± 0.001^{aB}	0.062 ± 0.003^{aB}
				pH			
T1	5.52 ± 0.01^{aA}	5.55 ± 0.03^{aB}	5.53 ± 0.02^{aB}	5.54 ± 0.03^{aA}	5.38 ± 0.02^{bA}	5.36 ± 0.2^{bA}	5.34 ± 0.03^{bA}
T3	5.52 ± 0.01^{bA}	5.62 ± 0.02^{Aa}	5.58 ± 0.04^{abA}	5.56 ± 0.02^{abA}	5.46 ± 0.03^{cB}	5.41 ± 0.02^{cdB}	5.37 ± 0.01^{dA}
T4	5.52 ± 0.01^{bA}	5.60 ± 0.03^{Aa}	5.57 ± 0.02^{abA}	5.58 ± 0.02^{abA}	5.56 ± 0.01^{cB}	5.45 ± 0.03^{dB}	5.43 ± 0.02^{dA}
				Total soluble solids (°Brix)			
T1	9.91 ± 0.05^{bA}	10.06 ± 0.03^{aA}	10.01 ± 0.05^{aA}	10.25 ± 0.02^{bA}	10.21 ± 0.05^{bA}	10.27 ± 0.02^{bA}	10.20 ± 0.06^{bA}
T3	9.89 ± 0.02^{bA}	10.03 ± 0.01^{bA}	10.04 ± 0.02^{abA}	10.15 ± 0.02^{aA}	10.17 ± 0.01^{aA}	10.16 ± 0.01^{aA}	10.25 ± 0.02^{aA}
T4	9.90 ± 0.01^{bA}	10.04 ± 0.02^{bA}	10.04 ± 0.02^{abA}	10.21 ± 0.01^{aA}	10.19 ± 0.02^{aA}	10.18 ± 0.03^{aA}	10.25 ± 0.02^{aA}
				Color (°Hue value)			
T1	59.08 ± 0.05^{aA}	59.41 ± 0.13^{aA}	58.46 ± 0.10^{aA}	58.26 ± 0.08^{aA}	57.84 ± 0.02^{aA}	56.14 ± 0.05^{aA}	55.25 ± 0.01^{aA}
T3	59.08 ± 0.05^{aA}	58.06b ± 0.11^{aA}	59.55 ± 0.11^{aA}	59.52 ± 0.05^{aA}	60.43 ± 0.03^{aB}	61.08 ± 0.04^{aB}	62.01 ± 0.02^{caB}
T4	59.10 ± 0.05^{aA}	58.11b ± 0.10^{aA}	59.58 ± 0.09^{aA}	69.02 ± 0.10^{aA}	60.46 ± 0.02^{aB}	61.18 ± 0.02^{aB}	62.67 ± 0.03^{caC}
				Chroma (C*)			
T1	35.18 ± 3.64^{aA}	35.73 ± 3.36^{aA}	35.29 ± 3.59^{aA}	33.19 ± 0.08^{baA}	30.37 ± 1.59^{bA}	30.50 ± 1.02^{4bA}	31.21 ± 1.10^{bA}
T3	35.19 ± 4.92^{aA}	34.40 ± 3.47^{aA}	35.11 ± 0.92^{aA}	34.18 ± 2.98^{aA}	32.89 ± 0.91^{bB}	32.18 ± 1.11^{bB}	33.71 ± 0.91^{bB}
T4	35.28 ± 3.85^{aA}	35.20 ± 4.13^{aA}	35.27 ± 2.89^{aA}	34.68 ± 2.78^{aA}	33.02 ± 1.01^{bB}	33.15 ± 1.05^{bB}	33.71 ± 0.82^{bB}
				Luminosity (L*)			
T1	45.09 ± 1.81^{aA}	45.28 ± 3.31^{aA}	46.51 ± 3.46^{aA}	45.53 ± 1.91^{aA}	44.71 ± 1.38^{aA}	42.65 ± 1.41^{bA}	43.56 ± 0.01^{bA}
T3	45.07 ± 1.08^{aA}	44.40 ± 1.23^{aA}	45.65 ± 2.01^{aA}	45.09 ± 1.01^{aA}	46.47 ± 2.15^{aB}	46.10 ± 0.85^{aB}	46.29 ± 0.75^{aB}
T4	45.09 ± 1.32^{aA}	44.51 ± 1.12^{aA}	45.95 ± 3.01^{aA}	45.19 ± 1.16^{aA}	46.17 ± 1.71^{aB}	46.28 ± 0.03^{aB}	46.69 ± 1.02^{aB}

Values are the means of three replicates. Lowercase letters (a, b, c) indicate significant differences between days of storage. Uppercase letters (A, B) indicate significant differences between treatments (p<005). T1 = Fresh-cut papaya with additives (1% $CaCl_2$, 0.1% iso-ascorbic acid and 0.05% sorbic acid), used as the control treatment. T2 = Fresh-cut papaya with additives (T1) and 1-MCP (1000 nL/L, 12 h at 10°C). T3 = Fresh-cut papaya with additives from whole papaya treated with 1-MCP (1000 nL/L, 12 h at 20°C). T4 = Fresh-cut papaya with additives treated with 1-MCP before and after cutting.

TSS increased (9.91 to 10.26 °Brix) in all treatments (Table 2). It is considered that an increase in TSS may occur in fresh-cut products since physiological events such as respiration and softening, responsible for polysaccharide degradation, are usually accelerated by cutting, and there is a generation of glycolytic intermediates such as hexoses (Massolo et al., 2019). For their part, Castillo-Israel et al. (2015) and Ergun et al. (2006) also detected an increase in the soluble solids content of fresh-cut mango and papaya due to the ripening process that continues after cutting, resulting in a decrease in the amount of starch and an increase in sugar content. Likewise, it has been reported that treatment with 1-MCP in whole fruits can increase, decreases, or causes no effect on the soluble solids content, depending on the species, variety, and storage condition (Thewes et al., 2023).

There were significant differences (p>0.05) between treatments in the °Hue, luminosity, and chroma values (Table 2). The color of the T3 and T4 samples was more orange, luminous, and saturated. It has been reported that the application by immersion of antioxidants and calcium chloride on fresh-cut fruit is an efficient process for stabilizing the color of fresh-cut fruits (Soliva-Fortuny and Martín-Belloso, 2003).

Values are the means of three replicates. Lowercase letters (a, b, c) indicate significant differences between days of storage. Uppercase letters (A, B) indicate significant differences between treatments (p<005). T1 = Fresh-cut papaya with additives (1% $CaCl_2$, 0.1% iso-ascorbic acid and 0.05% sorbic acid), used as the control treatment. T2 = Fresh-cut papaya with additives (T1) and 1-MCP (1000 nL/L, 12 h at 10 °C). T3 = Fresh-cut papaya with additives from whole papaya treated with 1-MCP (1000 nL/L, 12 h at 20 °C). T4 = Fresh-cut papaya with additives treated with 1-MCP before and after cutting.

1-MCP decreases ethylene production, avoiding the action of polyphenol oxidases (Xu et al., 2023). On the other hand, iso-ascorbic acid retards browning, and $CaCl_2$ stabilizes membranes against free radicals induced by lipid oxidation and by binding to phosphates and carboxylate groups of membrane surface phospholipids, maintaining cell wall rigidity (Picchioni et al., 1996). A study with fresh-cut lotus (*Nelumbo nucifera* Gaertn.) concluded that 1-MCP suppressed ethylene-induced physiological and biochemical

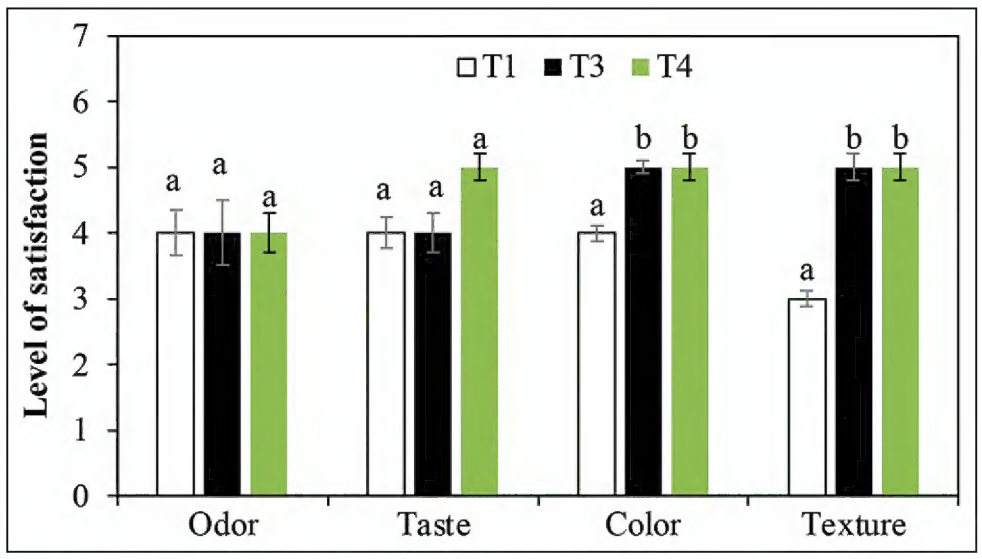

Fig 5. Sensory evaluation of fresh-cut papaya with additives (T1), fresh-cut papaya with additives from the whole papaya treated with 1-MCP (T3), and fresh-cut papaya with additives treated with 1-MCP before and after cutting (T4). Different letters indicate significant differences ($p<0.05$) between treatments.

reactions inhibiting enzymatic browning (Chen et al., 2022). In contrast, the decrease in luminosity and chroma of T1 may be correlated with increased translucency. Finnegan and O'Beirne (2015) linked the decreased color to the development of translucency in fresh-cut fruits, arguing that water-soaking intracellular masks the saturation and luminosity of color tones.

There is no significant difference ($p>0.05$) in the odor between treatments (Fig. 5); the judges gave scores of 4.0 (Like it slightly). T3 and T4 had higher texture and color scores than T1; however, T4 had the most elevated taste score (Like it very much).

Ergun et al. (2006) conducted a sensory evaluation of slices from intact 'Sunrise Solo' papaya untreated and treated with 1-MCP. The authors found significant differences ($p<0.05$) in odor, texture, and flavor. They concluded that papaya slices from intact untreated papaya showed values of 2.2 (poor-good to fair), and papaya slices from intact 1-MCP-treated papaya exhibited values of 3.2 (fair to good) at 6 days of storage at 4 °C. This experiment demonstrated that double 1-MCP application was adequate to maintain sensory attributes of fresh-cut 'Maradol' papaya for 10 days at 4 °C.

CONCLUSIONS

The results of this work indicate that the application of 1-MCP strongly influences the shelf-life of fresh-cut 'Maradol' papaya before and after cutting. 1-MCP caused the significantly lowest firmness loss, cell wall degradation, and translucency in fresh-cut papaya, thus preserving their texture. The microbiological analysis demonstrated the effectiveness of sorbic acid and 1-MCP in preventing the growth of total coliforms, mesophilic bacteria, molds, and yeast during storage. The application of additives ($CaCl_2$, iso-ascorbic acid, and sorbic acid) and 1-MCP before and/or after cutting in fresh-cut papaya is an excellent alternative to preserve the quality attributes of minimally processed papaya for up to 13 days at 4 °C.

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Author´s contributions

All authors contributed substantially to the writing and revising of the manuscript. Martina Alejandra Chacon-López, Flor Asalia Carrillo-Rodríguez, and Efigenia Montalvo-González designed the work, acquired, analyzed, and interpreted the data. Selene Aguilera-Aguirre, Libier Meza-Espinoza, and Efigenia Montalvo-González conducted the statistical analysis. María de Lourdes García-Magaña and Libier Meza-Espinoza conducted and analyzed the sensory analysis. Martina Alejandra Chacon-López, Efigenia Montalvo-González, and Elhadi M. Yahia critically reviewed, corrected, and edited the manuscript.

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